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The research conducted under this project has been an extension of an ongoing research effort for development of the Ocean SAmpling MObile Network (SAMON) Controller. The role of the Ocean SAMON Controller is to support the development of a distributed, high resolution and robust Autonomous Oceanographic Sampling Network (AOSN). The concept of the SAMON Controller is based on a multitude of inexpensive self-organizing autonomous vehicles releaes by a supply vessel in a certain region of the ocean.

The research conducted has focused on formulation of quantitative methods of statistical signal processing for calibration and estimation of oceanographic sensor signals (e.g., conductivity, depth, and temperature).

Two graduate students were partially supported by this AASERT grant.

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CALIBRATION AND ESTIMATION
OF OCEANOGRAPHIC SENSOR SIGNALS

FY '97 Augmentation Awards for Science and Engineering Research Training(AASERT) Program
Office of Naval Research Grant No. N00014-97-1-0786; augments Grant No. N00014-96-1-5026

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Abstract

The research conducted under this AASERT project has been an extension of an ongoing research effort for development of the Ocean SAmpling MObile Network (SAMON) Controller that was supported by the Office of Naval Research under Grant Numbers N00014-97-1-0786 and N00014-96-1-5026. The role of the Ocean SAMON Controller is to support the development of a distributed, high resolution and robust Autonomous Oceanographic Sampling Network (AOSN). The concept of the SAMON Controller is based on a multitude of inexpensive self-organizing autonomous vehicles released by a supply vessel in a certain region of the ocean. The objectives of the SAMON Controller project are as follows:

1. To implement a multi-vehicle self-organizing ocean sampling system simulator with a hierarchical autonomous control and inference-making architecture.
2. To quantitatively justify intelligent inference-making at each of the layers of the control hierarchy to circumvent limitations of sensor data and signal communications.

The research conducted under this grant has followed the second objective of the SAMON Controller project and focused on formulation of quantitative methods of statistical signal processing for calibration and estimation of oceanographic sensor signals (e.g., conductivity, depth, and temperature). Sensor signal processing at the individual local nodes in the controller network hierarchy reduces the channel bandwidth requirements which, in turn, allows improved network design leading to reduced data latency and enhanced fault tolerance.

Background and Motivation for the AASERT Research Program

All commercial and military shipping traffic must pass through shallow water when entering or leaving a port. In the post cold war era, the high density of marine traffic due to rapidly expanding international trade and commerce has lead to increased probability of naval confrontation in shallow water. It is well known [Ali, 93] that oceanographic variability of sensor signals is aggravated in a shallow water environment because of several factors including the interactions from ocean floor. Preparedness for confrontations and success of underwater military operations largely depend on efficacy of information communications between the undersea autonomous vehicles (AUVs) and the technical coordinator located on the shore. Sensor signals transmitted via sub-surface acoustic communications by AUVs located at several spatial locations are subjected to disturbances and noise from various sources.

The propagation of acoustic waves in the ocean is accompanied by fluctuations in the amplitude and phase of the signal received at spatial distances from the source. These fluctuations occur not only due to changing patterns of interactions with the ocean floor and surface (particularly in the shallow water environment), but also due to passages of the wave through time-varying inhomogeneities in the ocean medium. The variability in acoustic propagation accrues from the changing index of refraction of the medium which is induced by a variety of oceanographic processes covering a wide range of temporal and spatial scales. Depending on the spatial and temporal scales the sources of disturbances can be considered deterministic or stochastic. Examples of deterministic disturbances are waves in the order of

kilometers on the horizontal scale and of hundreds of meters on the vertical scale and in the order of days in the temporal scale. In contrast, smaller (spatial and temporal) scale phenomena such as those comprising internal waves and microstructure are generally considered to be stochastic. Sensor signals must be continuously calibrated to compensate for both deterministic and stochastic disturbances.

While any abrupt change in sensor data is easily detectable and can usually be eliminated by the built-in sensor signal validation procedure (e.g., limit check and rate check), it is the small changes and gradual degradation of sensor signals that requires special attention for timely detection, identification and compensation. The research has the potential to address these issues and to focus on formulation of quantitative methods for calibration and estimation of oceanographic sensor signals (e.g., conductivity, depth, and temperature). The research will potentially provide a novel technology of *Sensor Signal Processing* at the individual local nodes in the controller network hierarchy within the SAMON architecture.

Brief Overview of the Technical Approach

The technical approach to sensor signal calibration and estimation aims at compensation of both deterministic and stochastic disturbances by construction of an adaptive filter bank that has a nonlinear time-varying structure. Macroscopic models, such as those based on the wave equation or its approximation, of the underwater acoustic medium that characterize the mean sound velocity profile are useful for providing estimates of range/depth coverage for sonar communications. These models are categorized as deterministic because they do not describe the stochastic behavior of acoustic signal propagation. The autocorrelation and cross-correlation functions are commonly used to represent random fluctuations in acoustic intensity. For wide-sense stationary noise and signals, the (time-domain) correlation functions are isomorphic to (frequency-domain) spectral densities that can often be characterized by frequency partitioning. However, time-frequency analysis is necessary for nonstationary signals to obtain spatial/temporal locations of the signal contents at different scales.

Research Accomplishments

The concept of sensor signal calibration and estimation has been theoretically formulated and then experimentally verified on a set of laboratory data via fusion of the correlated data collected from spatially non-collocated and time-dependent signals of multiply-redundant sensors in one-dimensional fluid flow and has been reported in refereed conferences [Ray and Phoha, '00, '02] and archive journals [Ray and Phoha, '00, ,02]. The filter algorithm is built upon the principles of minimum-variance filtering and multi-level hypotheses testing. This approach, for example, is suitable for calibration of non-stationary correlated sensors located at different spatial points on the mooring of a mobile platform and has the potential of yielding significant benefits compared to those derived from conventional techniques of sensor signal processing. This cross-disciplinary research is both fundamental and applications-oriented in nature.

Future Research

For future research, we propose installation of spatially non-collocated sensors on the mooring of a mobile platform. The objective to have a number (say, four or more) of strongly correlated (but not necessarily redundant) signals for each type of sensors. The proposed research, at this stage, is limited to measurement calibration solely based on sensor signals. The future goal is to construct additional analytical measurements by using the information available from empirical, semi-empirical, and physics-based models as well as from other sensor signals. The underlying idea is to extract the temporal behavior of pertinent ocean variables (e.g., conductivity, depth, and temperature) averaged over a relatively small spatial region (e.g., on the order of tens of meters in the horizontal scale and on the order of meters in the vertical scale). This analysis will provide sufficient details for control of the AUVs and higher-level decision-making at the coordination level.

Refereed Conference Papers:

A. Ray and S. Phoha '00, "Calibration and Estimation of Redundant Sensor Signals and Analytical Measurements," *39th IEEE Conference on Decision and Control (CDC)*, Sydney, Australia, December 2000.

A. Ray and S. Phoha '02, "Calibration and Estimation of Redundant Signals," *American Control Conference*, Anchorage, Alaska, May 2002.

A. Ray and S. Phoha '02, "Fault Detection and Identification via Multi-level Hypotheses Testing," *International Federation of Automatic Control (IFAC) World Congress b'02*, Barcelona, Spain, July 2002.

Archived Journal Papers:

A. Ray and S. Phoha '00, "Calibration and Estimation of Redundant Signals," *Automatica*, Vol. 36, No. 10, October 2000, pp. 1525-1534.

A. Ray and S. Phoha '02, "Detection of Potential Faults via Multi-level Hypotheses Testing," *Signal Processing*, in press.

Doctoral Dissertations (Partly Supported)

Jeffrey Caplin, *Damage-Mitigating Control of Aircraft for High Performance and Life Extension*, Ph.D. Dissertation in Mechanical engineering, The Pennsylvania State University, University Park, PA, December 1998.

Eric E. Keller, *Real-time Sensing of Fatigue Crack Damage for Information-Based Decision and Control*, Ph.D. Dissertation in Mechanical engineering, The Pennsylvania State University, University Park, PA, May 2001.